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14. ABSTRACT

The research objectives of this project were to study and resolve some of the daunting problems that hinder the development of reliable general-purpose computer simulation programs, which are capable of reflecting precisely the dynamic behavior of distributed nonlinear systems, spanning the range from large joint-dominated space structures, to intricate electro-mechanical systems, to MEMS, as well as civil infrastructure systems, by conducting a comprehensive analytical and experimental study to investigate an important subset of the challenging issues.

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Final Report

ANALYTICAL AND EXPERIMENTAL STUDIES OF NONLINEAR SYSTEM MODELING AND SIMULATION

AFOSR GRANT NUMBER F49620-01-1-0125

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ANALYTICAL AND EXPERIMENTAL STUDIES INTO STRUCTURAL HEALTH MONITORING

Abstract

The research objectives were to study and resolve some of the daunting problems that hinder the development of reliable general-purpose computer simulation programs, which are capable of reflecting precisely the dynamic behavior of distributed nonlinear systems, spanning the range from large joint-dominated space structures, to intricate electro-mechanical systems, to MEMS, as well as civil infrastructure systems, by conducting a comprehensive analytical and experimental study to investigate an important subset of the challenging issues. The research was focused on developing *methods* and *procedures* suitable for use with structural response measurements, from flexible structural components and assemblages that may incorporate elements undergoing significant multi-dimensional nonlinear deformations. The research included carefully conducted experimental studies of generic types of nonlinearities likely to be encountered in aerospace structures. The experimental studies led to a better understanding of the physics of the underlying phenomena, thus allowing the development of suitable reduced-order mathematical models to characterize the essential features of the dominant structural characteristics. High-fidelity models (both parametric as well as nonparametric) were created that have the potential to provide predictive descriptions of nonlinear system behavior under arbitrary dynamic environments.

Accomplishments

Research activities of this project proceeded along two fronts: (1) an experimental phase involving the design and fabrication of an adjustable test apparatus for conducting studies on a generic "joint" element which incorporates important nonlinear characteristics such as nonlinear elastic properties, hysteretic characteristics and deadspace nonlinearities involving friction, and (2) an analytical phase focused on the development of a theoretical framework for processing experimental structural response measurements to develop nonlinear, reduced-order, high-fidelity mathematical models and to determine the response of such models under arbitrary dynamic environments.

1.0 EXPERIMENTAL STUDIES*:*

1.1 One-Dimensional Test Apparatus

An adjustable test apparatus was designed, fabricated, and assembled for the purpose of furnishing a convenient means of generating high-quality experimental measurements corresponding to a range of nonlinear phenomena with adjustable levels of polynomial-type nonlinearities as well as hysteretic behavior and deadspace nonlinearities incorporating Coulomb friction effects. A photograph of the major elements of the test apparatus is shown in Figure 1, and some preliminary experimental measurements

obtained from the test apparatus are exhibited in Figure 2 in which phase-plane plots of the hsyteretic nonlinear force is plotted versus the corresponding displacement for three different regimes of the motion.

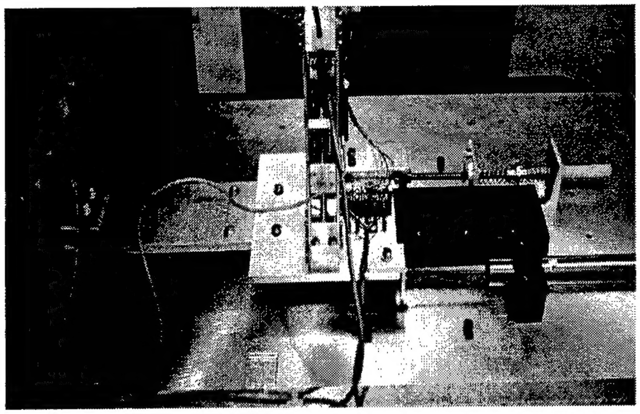


Figure 1. General view of one-dimensional re-configurable test apparatus.

In a subsequent phase of the research, the experimental measurements from the test bed were used to investigate the utility of an on-line identification approach developed by the PI and collaborators to obtain parametric models for physical systems incorporating hysteretic nonlinearities (Smyth et al, 2001).

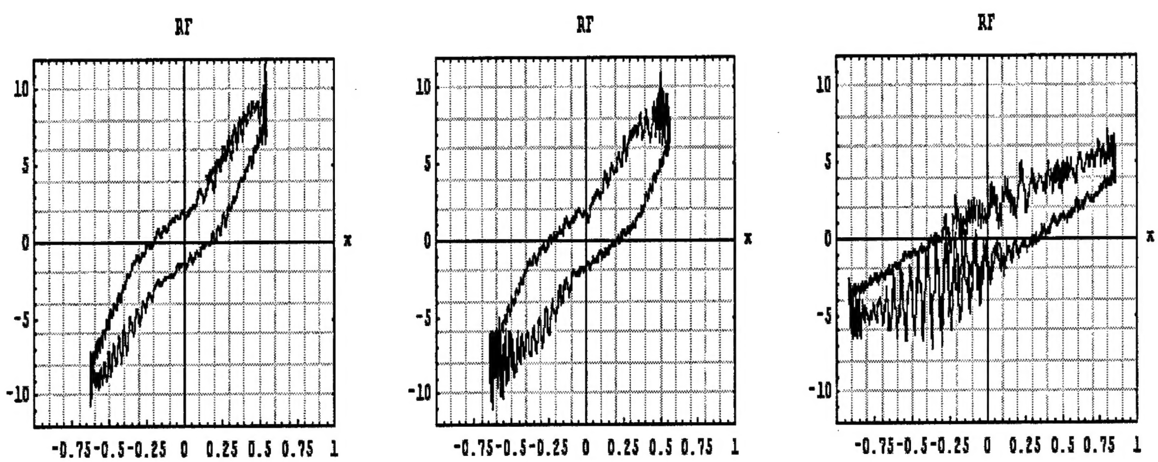


Figure 2. Nonlinear restoring force characteristics in three different ranges of motion.

The capability of the method under discussion to accurately capture time-varying hysteretic behavior is illustrated in Figure 3 where the identified system parameters as well as the tracking accuracy of the method are shown for some simulated data. Figure 3(a) shows the parameter convergence, and Figure 3(b) shows the phase-plane plot of the

exact and estimated nonlinear restoring force versus the element displacement. Notice that the value of the stiffness parameter θ_0 drops at t = 5 seconds from its original value of 5 towards the new value of 3.

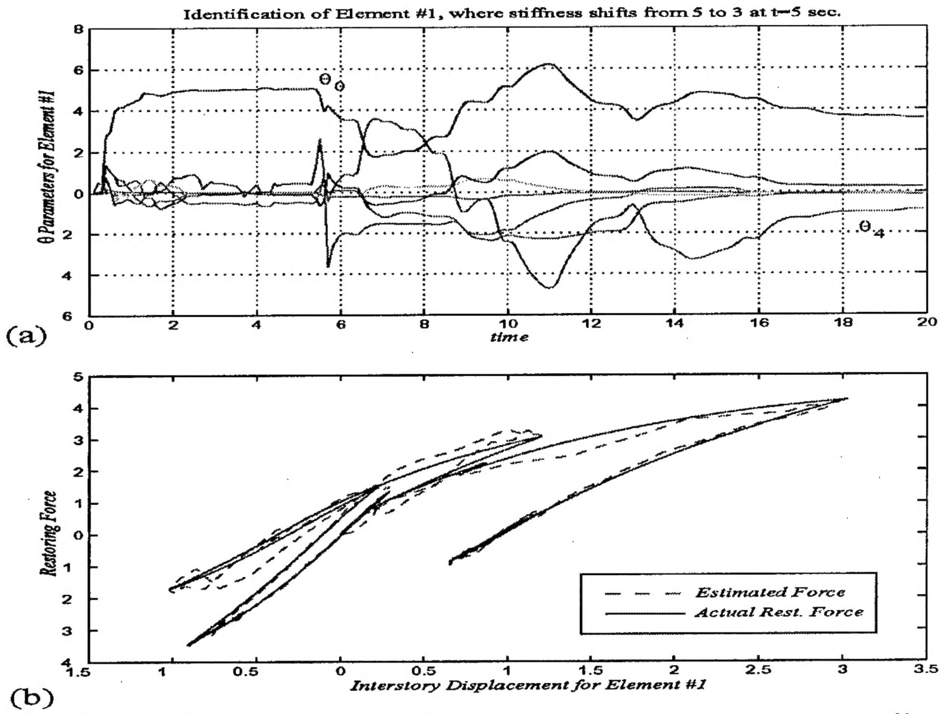


Fig. 3. Identification results for a hysteretic system with time-varying stiffness parameters. At t = 5 sec, θ_0 for the element drops from 5 to 3.

1.2 Two-Dimensional Nonlinear Element

By extending the adjustable one-dimensional test apparatus, a muti-axis nonlinear "joint" was designed and fabricated. The new apparatus furnishes a convenient means of generating high-quality experimental measurements corresponding to a range of nonlinear phenomena with adjustable levels of realistic nonlinearities, including hysteretic behavior and deadspace nonlinearities incorporating Coulomb friction effects. A photograph of the major elements of the multi-axis test apparatus is shown in Figure 4.

The experimental measurements from the sliding friction testbed, were used to evaluate the efficiency of the on-line identification approach, discussed above, to obtain parametric models (based on the generalized Bouc-Wen hysteretic model) for physical systems incorporating hysteretic nonlinearities.

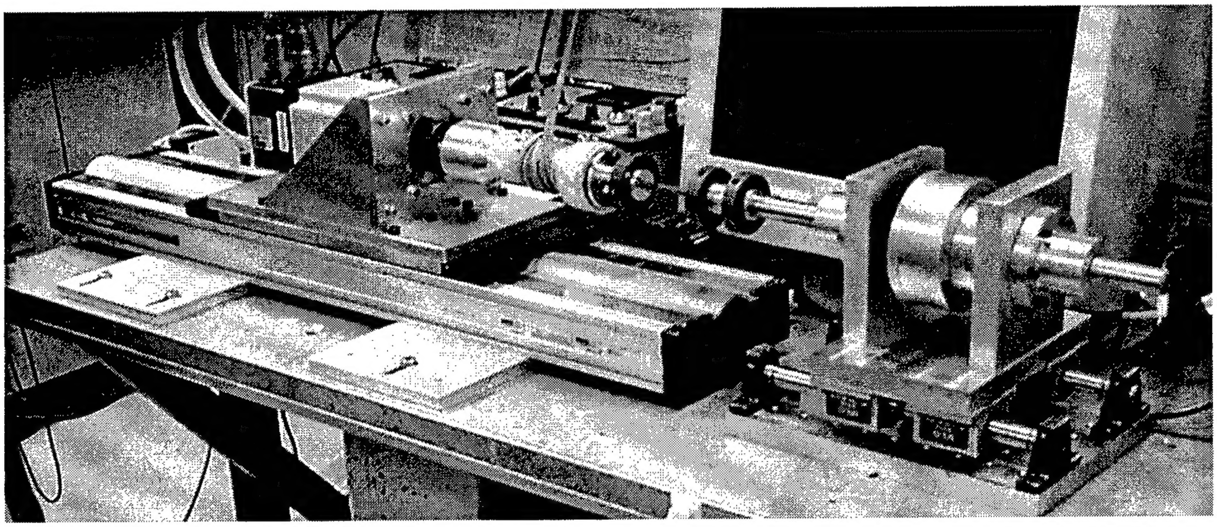


Figure 3: Photograph of multi-component hysteretic system with adjustable nonlinear characteristics

2.0 ANALYTICAL STUDIES

2.1 Equivalent Linearization for Nonlinear Systems Under Nonstationary Excitation

A new method based on equivalent linearization approaches was developed for estimating the nonstationary response of a class of nonlinear multi-degree-of-freedom systems subjected to nonstationary excitations. The highly efficient method is based on creating a compact analytical approximation of measured nonstationary excitation process data through use of a two-stage decomposition procedure. The analytical data condensation of the excitation process is performed in two stages; (1) by performing the Karhunen-Loeve spectral decomposition on the covariance matrix of the input random process to obtain the dominant eigenvectors, and (2) by fitting these eigenvectors with orthogonal polynomials to produce a truncated series of analytically approximated eigenvectors. The method has been demonstrated through simulation with synthetically generated excitation data as well as measured data from a real-world physical process. Although the decomposition procedure used can characterize very general input processes, because the equivalent linearization technique requires the Gaussian assumption of the response process, the constraint on applying this approach is similar to the constraints on all other equivalent linearization techniques. However, the additional freedom gained from being able to work with data-based nonstationary random processes is a significant addition to this area of research.

To illustrate the utility of the proposed approach, an example nonlinear SDOF system with a polynomial-type nonlinearity was simulated to test the proposed probabilistic response analysis method. First, a comparison was made with results using a synthetically generated nonstationary excitation similar to that in Roberts and Spanos (1990) and Sakata and Kimura (1980), and secondly, the system was simulated with a nonstationary data set.

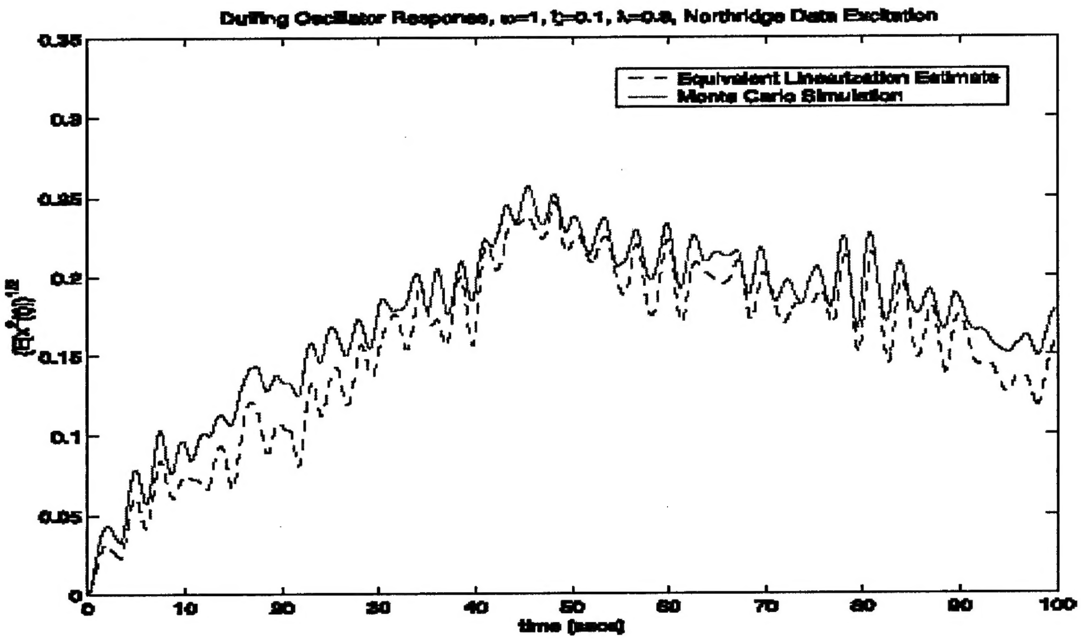


Figure 5. Nonstationary response of Duffing oscillator to earthquake excitation; comparison of analytical solution and Monte Carlo simulation

Prior decomposition techniques for nonstationary excitation processes have very often depended on making the restrictive assumption that the excitation is a stationary noise process multiplied by some deterministic envelope function. To demonstrate the proposed methodology, it was shown (see Fig 5) that the new approach can handle this special case of excitation processes. Further details of this study are available in the work of Smyth and Masri (2001).

Further details concerning the results of this research are available in the work of Smyth and Masri (2001).

2.2 Robust Adaptive Neural Estimation of Restoring Forces in Nonlinear Structures

The motivation for exploring adaptive techniques in the context of the modeling and control of nonlinear systems comes from the recognition that since structures behave non-linearly at various scale levels, the implementation of conventional fixed controller strategies may prove to be naive. Often, the governing response properties only exhibit themselves for the first time when subjected to strong excitation. As a result of this, control strategies should incorporate flexible adaptive identification schemes that can quickly capture and emulate the essential response signature of a structural system and react accordingly. Furthermore, the availability of estimation/identification techniques is crucial for the on-line control and monitoring of time-varying structural systems.

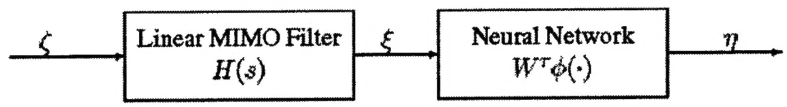


Fig 6: Block diagram of Volterra-Weiner Neural Network

The existing adaptive estimation/identification techniques suffer from two drawbacks: they assume that (1) the restoring forces applied to the system's elements are available for measurement and that (2) the differential equation driving these restoring forces can be parameterized as a linear combination of unknown constant parameters and known nonlinear terms.

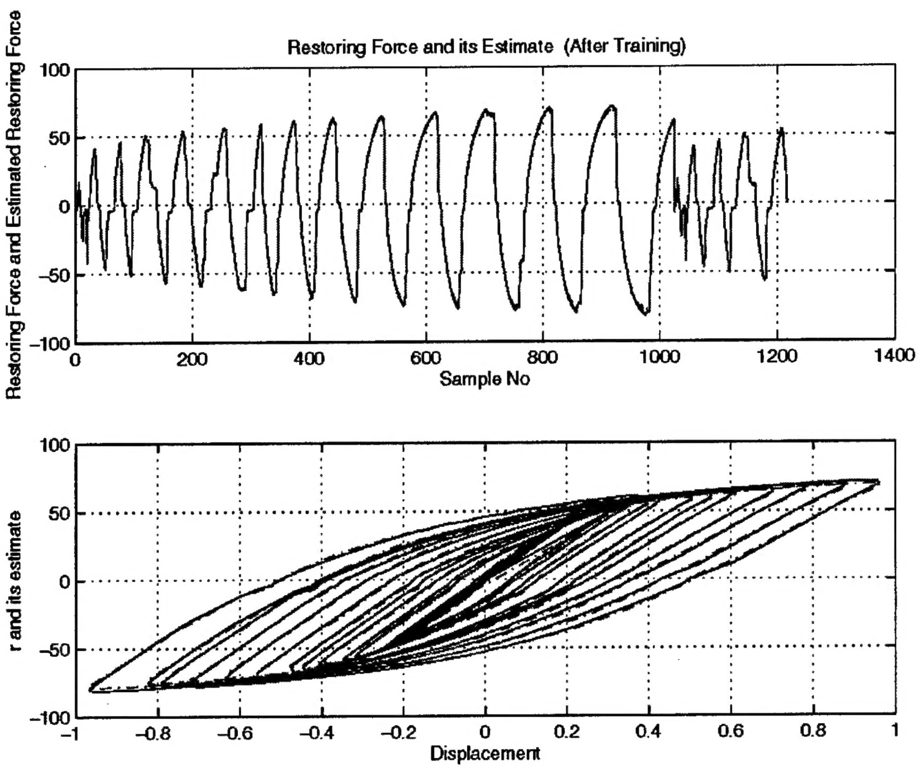


Fig 7: Degrading hysteretic forces and their estimate after neural network training.

With the above discussion in mind, the PI and collaborators (Kosmatopolous et al, 2001) have developed an efficient identification algorithm for handling general structural systems incorporating severe nonlinearities, including elements with time-varying hysteretic characteristics. This new methodology completely overcomes the above two problems. Specifically, a new approach is presented that solves the problem of estimating/identifying the restoring forces without assuming that the restoring forces are available for measurement, or imposing any restrictions on the nature of structure of the

restoring forces dynamics. The new approach uses appropriately adaptive filtering and estimation techniques and also makes use of the Volterra/Wienner Neural Network (VWNN), shown in Figure 6, which is capable of learning input/output nonlinear dynamical behaviors.

Simulations performed on a chain-like system under random excitation, as well as processing of experimental measurements from a reinforced-concrete structure as well as a steel structure, verified the efficiency of the proposed technique and demonstrated its utility. Sample results are shown in Figures 7 for experimental measurements corresponding to degrading hysteretic forces and their estimate after neural network training

Further details of this study are available in the work of Kosmatopoulos et al (2001).

2.3 Modeling and Analysis of Nonlinear MIMO Systems

As part of the effort to develop and evaluate a variety of tools and approaches for handling nonlinear multi-dimensional problems, a method previously developed by the PI and associates was used to analyze the response of a complex nonlinear distributed structural system. The structure was a modern long-span bridge in the Los Angeles region that was subjected to strong-motion earthquakes in the recent past. Using all the available experimental measurements from sensors mounted on and at the base of the bridge, the mathematical analysis of the unique data sets developed a reduced-order discrete system consisting of 10 inputs and 16 outputs.

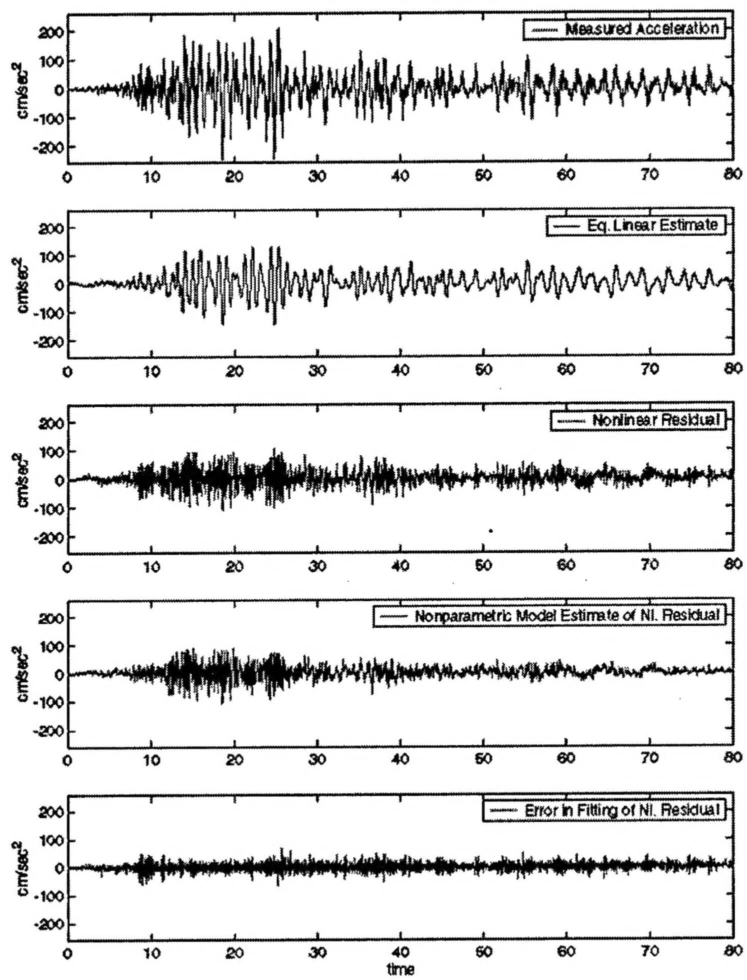
The analysis was conducted in two stages: In the first stage, a least-squares based time-domain identification approach was used to develop an equivalent linear MDOF system whose order is compatible with the available data set. This phase yielded the system matrices (inertia, damping and stiffness). Subsequently, in phase two, a nonparametric identification approach was employed to identify the residual nonlinear forces induced in the system. Sample identification results are shown in Figure 8.

Further details regarding this comprehensive study are reported in the work of Smyth et al, (2003).

2.4 Identification of the State Equation in Complex Nonlinear Systems

Building on the basic idea behind the *Restoring Force Method* for the nonparametric identification of nonlinear systems, a general procedure was developed for the direct identification of the state equation of complex nonlinear systems. No information about the system mass is required, and only the applied excitation(s) and resulting acceleration are needed to implement the procedure. Arbitrary nonlinear phenomena spanning the range from polynomial nonlinearities to the noisy Duffing - van der Pol oscillator (involving product-type nonlinearities and multiple excitations) or hysteretic behavior such as the Bouc-Wen model can be handled without difficulty. In the case of polynomial-type nonlinearities, the approach yields virtually exact results for sufficiently rich excitations. For other types of nonlinearities, the approach yields the optimum (in

least-squares sense) representation in nonparametric form of the dominant interaction forces induced by the motion of the system.



Fgure 8: Identification of the nonlinear forces in a MIMO nonlinear system having 10 inputs and 16 outputs, under the action of nonstationary random excitations.

Several examples involving synthetic data corresponding to a variety of highly nonlinear phenomena have been investigated to demonstrate the utility as well as the range of validity of the proposed approach. The acceleration of the hysteretic system was modeled in a non-parametric way involving the use of a set of basis functions of the system's excitation, velocity and displacement (linear, quadratic and cubic powers). Even though the actual (hysteretic) model is not included in the model structure used for identification, the results of the identification procedure under discussion yielded fairly accurate estimates of the complex nonlinear behavior of the system.

To evaluate the validity of the identification results, the same (exact) hysteretic model was subsequently subjected to a different excitation than what was used for its identification. Results showed that good fidelity is provided by the identified model in emulating the nonlinear behavior of the actual (exact) system.

Further details regarding this study are available in the work of Masri et al (2003).

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Publications:

The following papers, which are supported in part by this research effort, have been published, and are listed in chronological order:

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Interactions/Transitions:

Results of the research are directly applicable to modeling and health monitoring of civil infrastructure systems as well as general nonlinear systems encountered in the aerospace field.

Extensive collaborations with several researchers at different academic institutions were performed, and several published technical papers resulted from these interactions.

New Discoveries, Inventions, or Patent Disclosures: None

Honors/Awards: None

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